MACROSCOPIC FEATURES OF LIGHT HEAVY-ION FISSION REACTIONS

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Abstract

Global macroscopic features observed in the fully-damped binary processes in light di-nuclear systems, such as limiting angular momenta, mean total kinetic energies and energy thresholds for fusion-fission processes ("fission thresholds") are presented. Their deduced systematics are consistent with that obtained for heavier systems and follow a fusion-fission picture which can be described by a realistic rotating liquid drop model considering diffuse-surface and finite-nuclear-range effects.

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In recent years, light heavy-ion collisions have been extensively studied over a wide range of low bombarding energies ($E_{lab} \leq 10$ MeV/nucleon) for various target+projectile combinations, thus well establishing that the fusion-fission process (FF) in **light** di-nuclear systems[1−7] (in the A $\leq$ 60 mass region) has to be taken into account when exploring the limitations of the complete fusion (CF) process at high excitation energies and large angular momenta. The main extracted properties of the fully energy damped processes for these light heavy-ion reactions have been well explained with several different statistical descriptions (based for example either on the saddle point picture[5] or on the scission point formalism[4]), indicating that FF is significant in this mass region. In particular FF calculations[4−7] have been found successful to describe experimental observables, such as mass, charge and energy distributions of the fully-damped yields of most if not all the studied systems. However a more systematic understanding of the total fusion process is still needed as soon as the FF yield is found non negligeable due to a lowering of the fission barriers. By using the basic hypothesis of the rotating liquid drop model[8] (LDM), diffuse-surface[9] and finite-nuclear-range effects have been found to be of crucial importance[5,10,11] to account for experimental FF cross sections within the framework of the early steady-state theory of Bohr and Wheeler. We will show in this Brief Report that a global macroscopic description of the main features of FF needs also these effects to be incorporated for **light** nuclei.

In the so-called first regime of the fusion process (region I), near the Coulomb barrier, the fusion cross section is determined by the barrier penetration probability and, for incident energies up to around twice the Coulomb barrier energy, the reaction cross section is mainly dominated by the CF yield. At higher incident energies (in region II), the CF yield tends to saturate due to the activation of other competing mechanisms such as deep inelastic (DI) collisions. Heavy-ion resonances and DI orbiting processes have also been shown to occur for partially damped and large near-grazing partial wave components of the incident flux[12] at incident energies higher than the bending energy where the CF cross section begins to saturate. The DI processes can lead the two interacting nuclei to form a di-nuclear complex, from which they can either fuse into a compound nucleus (CN) after complete equilibration

of all the degrees of freedom, or escape from the ion-ion potential well, producing a damped orbiting process. The interplay between the nuclear potential and the friction forces, which control the damping of both the kinetic energy and the angular momentum, will determine whether fusion or faster binary decay processes may occur. It has been also shown that the degree of competition between these two classes of processes is correlated to the number of open channels (NOC) available for the decay of the di-nuclear system[12,13]. Large NOC tend to favour the occurence of statistical processes with regard to faster mechanisms which retain the memory of the entrance channel in sharp contrast to the theory of Bohr and Wheeler.

In region III, at higher bombarding energies, the survival probabilities of both the target and the projectile are drastically suppressed during the collision and consequently the incomplete fusion components become significant. In this energy regime the measured CF cross sections show a rapid decrease which corresponds to an experimental limiting angular momentum. The compiled limiting angular momenta have been taken from Ref.14 or extracted from more recent CF excitation measurements measurements[15−20] which have all shown a critical angular momentum limitation. These maximum angular momentum data, due to a general instability of the composite system against fission, lie systematically well below the LDM angular momentum limit[8] (dashed line) for which the fission barrier vanishes. The data are found, however in agreement with the predictions of a modified version of LDM[10] which includes finite-range corrections of the nuclear interaction by means of a Yukawa-plus-exponential attractive potential[9] and diffuse surface effects[10]. The finite-range corrections produce for each angular momentum a lowering of the fission barrier due to the attractive forces between surfaces of the two nascent fragments at the saddle point. The magnitude of the reduction in fission barriers which increases with decreasing A is one of the main reason why FF has been recently investigated for **light** di-nuclear systems. The vanishing fission barriers displayed in Fig.1 have been calculated for the beta-stable nuclei (solid line) using the finite-nuclear-range LDM (FRLDM) extended to rotating nuclei by Sierk[10]. In this model[10] the attractive force of finite-range was permitted between the nascent fragments

at the saddle point in order to reproduce the experimentally deduced angular-momentum dependent barriers[10,11]. The increasing discrepancy with increasing mass number (in the vicinity of A $\leq$ 100 where the Businaro-Gallone transition is expected to occur) is observed in Fig.1 and interpreted by the possible occurence, in heavier systems[20], of fast-fission and quasi-fission mechanisms (considered as an equivalent to a DI orbiting process for lower mass number) competing with the statistical FF for the highest partial waves. In this high-energy domain, the compound system is formed at very high excitation energy and high angular momenta inducing quite large deformation effects in the evaporative cascade. In addition to the evaporation of neutrons, protons and alphas, the fused system in this region may undergo binary decay through the emission of complex fragments and intermediate mass fragments[21] and/or an asymmetric fission process[5]. Finally in the intermediate energy regime ($E_{lab} \geq 40$ MeV/nucleon) , the nuclear system before its complete dissassembly (multifragmentation) is capable of reaching an upper limit for the temperature at which a "vaporization mechanism" into light particles may occur.

Although the FF cross section in light heavy-ion reactions represents only a small fraction (less than 5-10 %) of the total reaction cross section, several systems were investigated in detail[1−7] and characteristic macroscopic features were clearly established[5]. The statistical origin of the observed fully-damped fragments has been recently established for several light di-nuclei such as ^{19}F and ^{20,21}Ne (investigated by means of the ^{9}Be,^{10,11}B+^{10}B reactions respectively[15,16]) ^{27,28}Al (investigated by means of the ^{16}O+^{11}B, ^{17}O+^{10,11}B ^{18}O+^{10}B and ^{19}F+^{9}Be reactions respectively[7]), ^{47}V (investigated by means of the ^{35}Cl+^{12}C, ^{31}P+^{16}O and ^{23}Na+^{24}Mg reactions[6]) and ^{48}Cr (investigated by means of the ^{24}Mg+^{24}Mg, ^{36}Ar+^{12}C and ^{20}Ne+^{28}Si reactions[22]) as populated by different entrance channels having very different mass-asymmetries, thus verifying whether the Bohr hypothesis is fulfilled or not. In other cases for which this has not been experimentally possible, the experimental data have been compared to FF predictions[1,5].

Generally all of the observables, including the fragment total kinetic energies (TKE), obtained in these experiments[1,5−7,22] are very well described by a FF picture using the sta-

tistical model[4,5]. We have compiled in Fig.2 the mean TKE values, of the symmetric fission fragments produced in light heavy-ion systems. The systematics due to Viola[23] (dashed lines), which predicts a linear dependence of TKE with the Coulomb parameter $Z^2/A^{1/3}$, is capable of describing the data set available in the literature[23,24], but fails in the case of low Z fissioning nuclei as shown by the insert of Fig.2. Due to the diffuse nature of the nuclear surfaces of light nuclei and the associated perturbations of the necking degree of freedom consistent with both the droplet model[25] and FRLDM[10] calculations, a change in slope at low values of $Z^2/A^{1/3}$ (see insert of Fig.2) leading to vanishing TKE values as Z approaches zero may be expected. This effect is illustrated by the solid curves drawn in Fig.2 which has been calculated by the following formula :

$$TKE = Z^2/(aA^{1/3} + bA^{-1/3} + cA^{-1})$$

where the values of the parameters are a = 9.65 MeV^{-1}, b = -58.1 MeV^{-1} and c = 188 MeV^{-1} respectively as a result of a simple weighted least-squares fitting procedure. The mass dependence of this formula is justified by the fact that for spherical nuclei the extension of the charge distributions around their centers has this type of dependence as required by the droplet model[25] to take the diffuseness into account in LDM[8]. Although second-order effects such as nuclear structure (mainly shell effects) and pairing effects have not been taken into account, this new simple universal expression of TKE, valid for a very wide range of fissioning systems extended to the lighter ones, appears to be quite useful for its prediction capabilities.

At this point it is interesting to note that all the data available for light systems were obtained from FF yields. Although the TKE values were extracted at the threshold energies for the process, a small contribution of the rotational energy term is included. This contribution is expected to be not very significant in cases where the effective moment of inertia in the double-spheroid approximation of the saddle point is quite large and the fusion critical angular momentum at the threshold is rather small. In this context, one has

to admit that some of the small discrepancies observed for medium weighted nuclei ($200 \leq Z^2/A^{1/3} \leq 500$) can possibly be explained by this additional rotational component present in the experimental points. However, it is still relevant to do the comparison with heavier, more fissile systems data as those previously compiled by Viola et al.[23].

The measurements of the excitation functions for the total fission cross sections for the ^{10}B+^{10}B (Ref.3), ^{18}O+^{10}B (Ref.7), ^{35}Cl+^{12}C (Ref.4 and 24) and ^{16}O+^{40,44}Ca (Ref.1) reactions have shown that the FF cross sections rise rapidly with increasing bombarding energies and then more slowly at higher energies. When plotted as a function of $1/E_{cm}$ the excitation functions present a simple linear relation similar to the case of CF processes in region I (see Ref.12 or 13 for instance). This behaviour is a characteristic signature of a statistical CN emission and well predicted by statistical model calculations[1−7]. These calculations start with the CN formation hypothesis and then follow the decay of the system by first chance binary fission or light-particle emission and subsequent light-particle or photon emission. Since the LDM[8] predicts too high fission barriers, the mass-asymmetric fission barriers are calculated following the procedure outlined in FRLDM[10] in order to incorporate diffuse-surface and finite-nuclear-range effects. The transition-state method has been most notably successful in accounting for many of the observed features of the fission process in the **light** di-nuclear systems[5] as well as for the emission of complex fragments from heavier compound nuclei[21].

Based upon the available FF excitation function data (including the fully-damped yields data for the ^{12}C+^{24}Mg,^{28}Si and ^{14}N+^{28}Si reactions taken from Ref.26 and the fission data for the ^{35}Cl+^{52}Ni reaction[27]), it has been possible to extract experimental values of "fission threshold" ($E_{fission}^{threshold}$) which correspond to the intersection of the FF cross section curve with the ($1/E_{cm}$) axis. The experimental data shown in Fig.3 indicate that $E_{fission}^{threshold}$ has a linear relationship with the CN Coulomb parameter $Z^2/A^{1/3}$. The reduced values of $E_{fission}^{threshold}/(Z^2/A^{1/3})$ for different nuclei ranging from mass 20 to mass 97, plotted as a function of x the LDM fissility parameter[8] , appear to be pratically constant within the error bars. Although there exists no simple relashionship with the FF macroscopic energies, these

“fission thresholds” might be possibly associated to fission barriers after consideration of the contribution of the centrifugal term (as shown for the TKE systematics) and also that of the saddle point deformations which might be non negligeable at these incident energies. The lack of any obvious dependence from system to system is not yet well understood. This study calls for new experimental works in the $0.35 \leq x \leq 0.50$ fissility region for which the Businaro-Gallone transition from asymmetrical to symmetrical fission is expected to occur. In the meantime a more theoretical approach of the fission barriers in this mass region will surely require more detailed excitation function measurements for “sub-threshold” bombarding energies in order to check the “universality” of the complex fragment emission as proposed very recently by Moretto[21] for more massive systems. Experimental studies are being currently undertaken.

In summary, a systematic examination of the main general characteristics of the fusion-fission process (limiting angular momenta, mean total kinetic energies and “fission thresholds”) in light heavy-ion reactions suggests that the rotating liquid drop model can be extended for very **light** nuclei when the diffuse nature of nuclear surfaces and finite-nuclear-range effects have been explicitly taken into account as previously proposed for heavier nuclei[10,21]. Although more refined theoretical studies will have to be undertaken to investigate second order effects (such as nuclear structure effects, proximity and/or viscosity effects, the temperature dependence of the surface energy, ...), this systematic study suggests that a very crude macroscopic picture of nuclear matter at high excitation energy and angular momentum remains a reasonable way to describe the collective nature of hot nuclei as light as the ^{19}F and ^{20}Ne nuclei which can be considered as remnants of liquid droplets.

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FIGURES

Fig.1 : Experimental (points) and calculated LDM[8] (dashed line) and FRLDM[10] (solid line) limiting angular momenta for fusion as a function of the CN mass number A_{CN} of beta-stable nuclei. The solid points have been previously compiled in Ref.14. The open points correspond to the following reactions (compound systems): ^{10}B+^{9}Be (^{19}F) and ^{10}B+^{10,11}B (^{20,21}Ne) taken from Refs.15-16, ^{28}Si+^{12}C,^{40}Ca (^{40}Ca,^{68}Se) from Refs.17-18, ^{16}O+^{40}Ca (^{56}Ni) from Ref.19 and, ^{40}Ca+^{40}Ca (^{80}Zr) from Ref.20.

Fig.2 : Most probable mean TKE release in fission as a function of the Coulomb parameter $Z^2/A^{1/3}$ of the fissioning nucleus. Open triangles have been taken from previous existing compilations[23−24]. Experimental solid points have been compiled from the data given in Refs.3-7,15-16,19-20. The dashed lines are the result of the Viola systematics[23] whereas the solid lines are the result of the fitting procedure discussed in the text.

Fig.3 : Experimental "fission thresholds" divided by the Coulomb parameter $E^{threshold}_{fission}/(Z^2/A^{1/3})$ plotted as a function of the fissility parameter x for the indicated reactions and compound systems.